Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System

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LONG-TERM GOAL

The long-term goal of this project is to improve our capability to predict the inherent spatial and temporal variability near the Philippine Straits, and thus contribute to the development of reliable prediction systems.

OBJECTIVES

The primary focus is to provide a comprehensive understanding of the remote and local factors that control the meso- and submesoscale features in and around the Philippine Archipelago Straits. The main objectives are:

- to explore the effects on the Philippine Straits of remote forcing from the equatorial waveguides, throughflows, and adjacent seas mesoscale dynamics;
- to estimate the effects of local winds in generating meso- and submesoscale variability;
- to quantify the role of barotropic tidal forcing in promoting side wall eddies and internal tides;
- to study the role of abrupt changes in bathymetry in generating submesoscale variability; and
- to investigate the impact of variational data assimilation on the simulation and predictability of the meso- and submesoscale circulation features.

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APPROACH

The approach for accomplishing the proposed objectives is model simulation using ROMS (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009) and its comprehensive ocean prediction and analysis system (Moore *et al*., 2004, 2009, 2010). Tidal forcing is imposed using available global OTPS model.

ROMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski *et al*., 2004; Warner *et al*., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom. Several adjoint-based algorithms exists for 4-Dimensional Variational (4D-Var) data assimilation (Moore *et al*., 2010; Powell *et al*. 2008; Muccino *et al*., 2008; Di Lorenzo *et al*., 2007), ensemble prediction, adaptive sampling, circulation stability (Moore *et al*., 2004), and sensitivity analysis (Moore *et al*., 2009).

Two regional, nested grids have been built: coarse (5 km), and fine (2 km). The initial and lateral boundary conditions are from the 1/12° Global HYCOM with NCODA (provided by Joe Metzger and Harley Hurlburt), atmospheric forcing is from NOGAPS 3-hours, half-degree resolution, and the tidal forcing is from the global OTPS model.

WORK COMPLETED

Real-time forecasts without data assimilation in the Philippine Archipelago were carried out in support of the *Exploratory* cruise (June 2007), *Joint* cruise (December 2009), *Regional IOP-1* cruise (January 2008), and *Regional IOP-2* cruise (February-March 2009). Each prediction cycle, updated daily, was run for 9 days (4-day hindcast and 5-day forecast). The model was initialized 4 days prior to the forecast cycle starting day to use reanalyzed atmospheric and boundary forcing. Real-time forecasts can be found at http://www.myroms.org/philex.

A tidal harmonic analysis on free-surface and currents was carried out to validate and compare ROMS against OTPS fields. The results show that the barotropic tides are well simulated in ROMS except in the interior of the Philippine Archipelago for the 5km grid. This is improved in 2km grid indicating that finer resolution is needed to resolve the inter-island passages. This analysis was also used to study the structure and generation mechanisms of internal tides. We found that internal tides are generated in the Sulu islands chain and propagate in both directions towards the Sulu Sea to the north and the Celebes Sea to the south (Zhang *et al.*, 2009).

As a preamble to the data assimilation experiments, optimal perturbations and adjoint sensitivity analysis were performed to identify the validity of the tangent linear approximation, assimilation time windows, and observational operators. Three different adjoint sensitivity metrics have been computed for the Mindoro, Bohol, Surigao, and San Bernardino Straits. They are: transport, velocity anomaly, and temperature anomaly. Results indicate that bathymetry, temperature and velocity are crucial to obtaining a good estimate of transport.

RESULTS

Table 1 shows the observed *in-situ* data in the Philippine Archipelago from various sources that have been processed for data assimilation into ROMS. The other data that is available for assimilation includes satellite SST (Micro-Wave and IR), satellite altimetry, and HF radar currents. Notice that the towed and moored ADCP data will not be used for data assimilation because its time span is not long enough to remove the high frequency tidal signal. However, this ADCP data will be used to evaluate the solutions and compute circulation skill metrics.

Table 1. Status of data collected during the Exploratory, Joint, Regional IOP-1, and Regional IOP-2 cruises: P processed for data assimilation, M instrument malfunction, W to be processed, X not suitable for data assimilation.

Cruise	CTD	Towed ADCP	Moored ADCP	Glider	APEX Floater	Underway Surface T, S	Towed CTD	Time
Exploratory	P	X	X	P	P	W	-	Jun 2007
Joint Cruise	P	X	X	-	-	P	-	Dec 2007
Regional IOP-1	P	X	-	P	P	P	P	Jan 2008
Regional IOP-2	P	X	-	M	W	W	W	Feb-Mar 2009

Several 4D-Var data assimilation experiments have been carried out using satellite SST and altimetry and *in-situ* temperature and salinity as described in Table 1. The assimilation improved the model-data fit and prediction skill. Figure 1 shows the RMS error between model and observations for the *Exploratory* Cruise (June 2007). It shows the values for the real-time, non assimilative run (blue curve), 4D-Var data assimilation analysis (red curve), and forecast from the model initialized with the best initial conditions from data assimilation (black curve). The temperature correction is between 1.0 and 2.0 Celsius. On the other hand, the correction for salinity is much larger at nearly 0.2. Notice that the forecast initialized from the analysis (black curve) has better skill than the control one (blue curve). The larger salinity correction is typical for all cruise periods. This is primarily due to the incorrect fresh water sources from the lateral boundary conditions from the global HyCOM model and uncertainties in the surface fresh water flux (E-P). We have also found that the data assimilation extends the predictability in the region to 2-3 weeks.

Analysis of the results (not shown) indicates that the data assimilation is able to remove excessive salt in the Sulu and Bohol Seas and Leyte Gulf. In the Pacific Ocean, the assimilation removed excessive salt from the surface, and created a more pronounced subsurface salty layer. Improvements are also noticeable in the Sibuyan Sea. Overall, the RMS error in salinity is decreased from 0.17 to 0.09 by assimilation. Similarly, the RMS error in temperature is decreased from 2.1 to 1.3 Celsius.

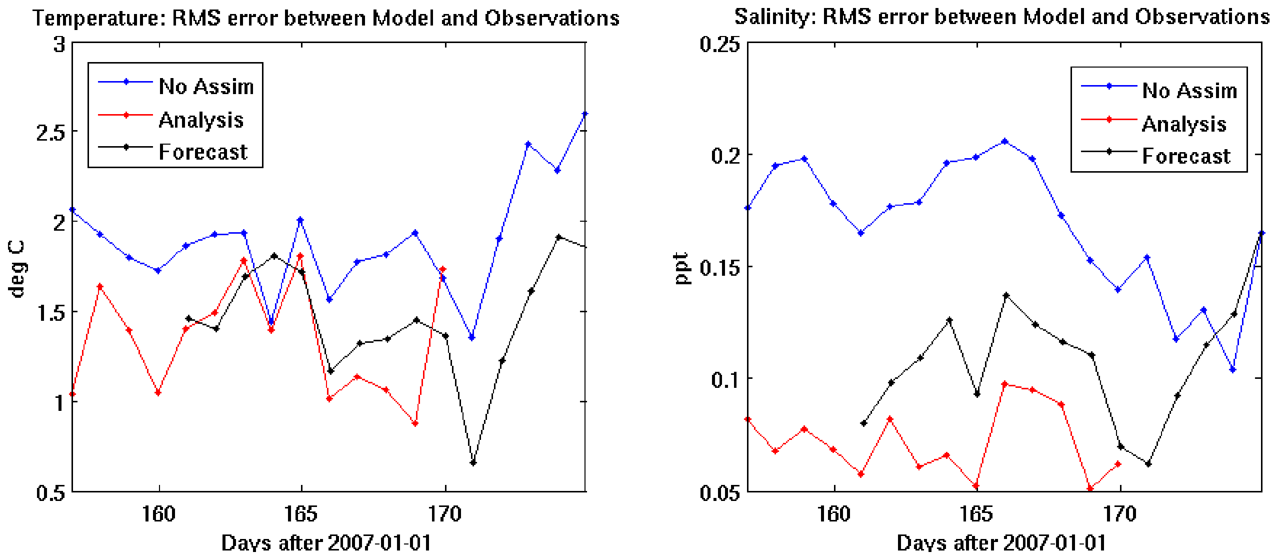

Figure 1. Temperature and Salinity RMS error between model and observations.

One of our major constraints in our simulation is the water properties modification in depth water which causes the model to over mix the entire water column. This modification deteriorates the solution after 2-3 weeks beyond the data assimilation. We have been able to track the problem back to the lateral boundary conditions in HyCOM daily fields. Figure 2 shows the T-S diagrams for two different versions of HyCOM for the *Exploratory* and *Regional IOP-1* cruise periods. The top panels (Fig. 2a,b) show the T-S between observations (red dots) and model (blue dots) for an old version HyCOM whereas the bottom panels (Fig. 2c,d) show the newer version. The differences between old and new are due to the chosen assimilation strategy in HyCOM. Notice that all panels show spurious deep water masses below 15°C and above a salinity value of 34.3. This spurious forcing at the boundary is propagated to the interior domain and causes the N^2 (Brunt-Vaisala frequency) to become unstable, which in turn forces excessive vertical mixing in ROMS.

The effects of the over mixing in ROMS is better illustrated in Figure 3. The top left panel (Fig. 3a) shows the T-S properties for the observations colored according to their location in the Philippine Archipelago (Fig. 3c). The top right panel (Fig. 3b) shows ROMS solution. It is very clear from the almost strait T-S curves that excessive mixing is taking place. The vertical parameterization scheme in ROMS is able to remove the spurious water masses that enter the domain at the cost of over diffusing simulated temperature and salinity. This requires substantial correction through data assimilation to restore the thermocline.

We are currently looking for alternative lateral boundary conditions for this application of the Philippine Archipelago. We are now processing the boundary data from 1/12 degree resolution global Mercator which includes data assimilation with the hope that this will improve our state estimation.

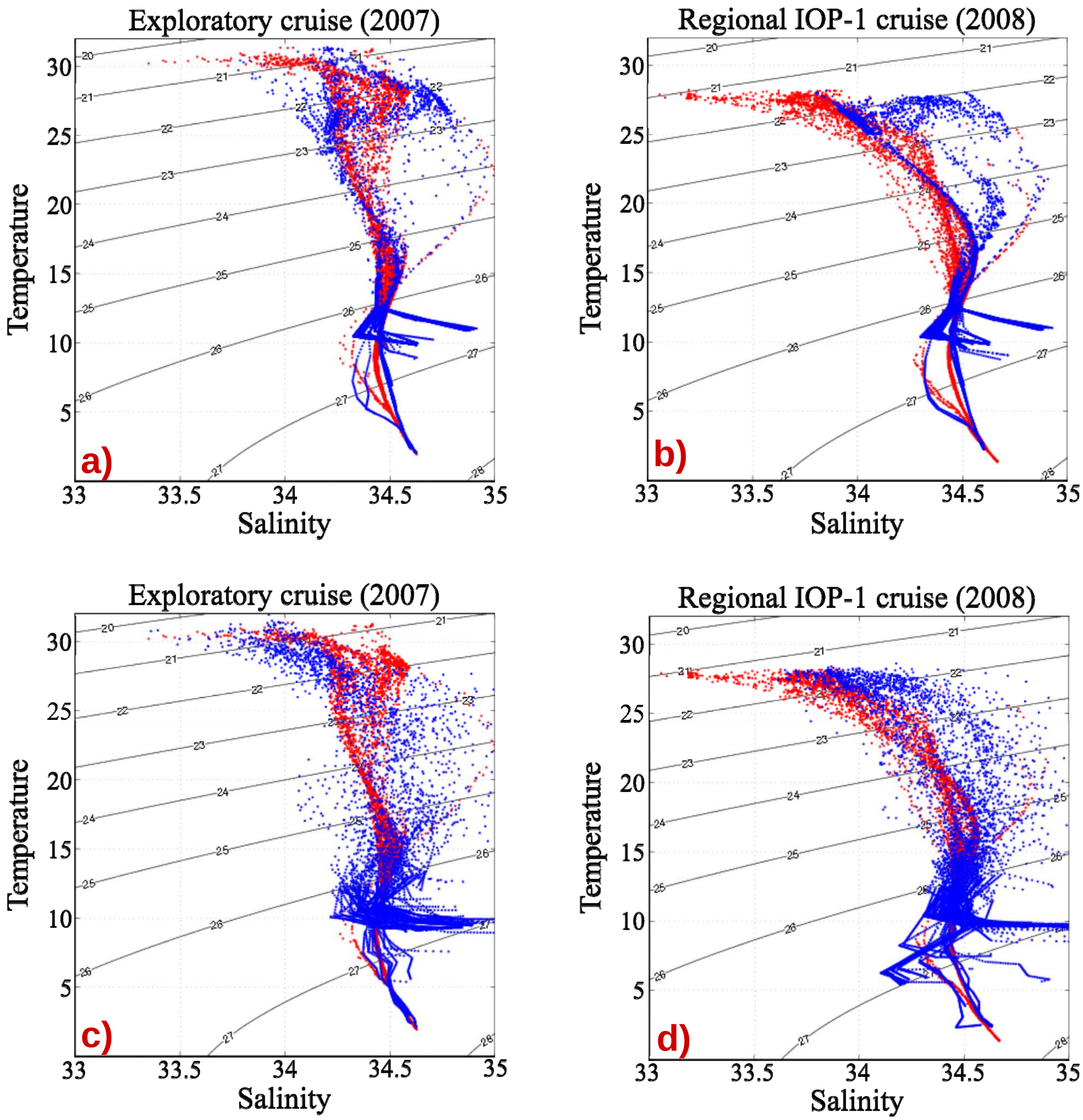

Figure 2. Temperature and salinity diagram between observation (red dots) and HyCOM (blue dots): a) Exploratory Cruise and HyCOM old solution, b) Regional IOP-1 and HyCOM old solution, c) Exploratory Cruise and HyCOM new solution, and c) Regional IOP-1 and HyCOM new solution. The old and new solutions refer to different assimilation strategies witin HyCOM.

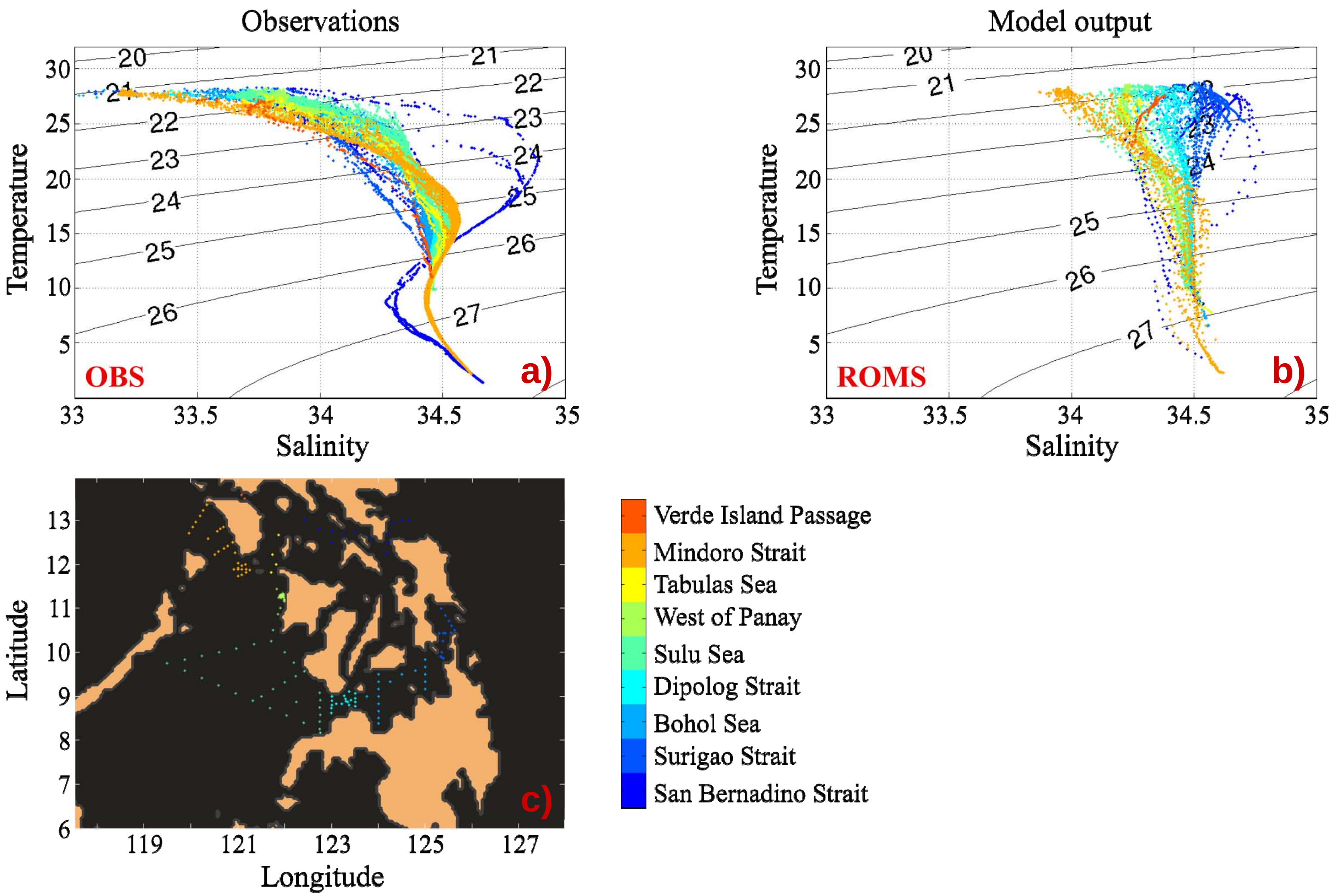

Figure 3. Temperature and salinity diagrams for observations and ROMS solution: a) in-situ observations, b) ROMS solution, c) color code map of observation locations. The colors in the top panels correspond to the locations in the map.

IMPACT/APPLICATIONS

This project will advance our scientific understanding of the generation dynamics and predictability of meso- and sub-mesoscale eddies near straits.

TRANSITIONS

None.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (Arango) closely collaborates with A. Moore (data assimilation and adjoint-based algorithms) at University of California, Santa Cruz, B. Powell (data assimilation applications) at University of Hawaii at Manoa, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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